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AC 2009-1451: A FRAMEWORK FOR DEVELOPING A COHESIVE SET OF REMOTE LABORATORIES FOR DISTRIBUTED DISTANCE LEARNING SETTINGS

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A Framework for Developing a Cohesive Set of Remote Laboratories for Distributed Distance Learning Settings

Abstract

The use of distance learning technology in distributed educational environments has allowed engineering courses to be delivered to locations and populations that have historically not been afforded opportunities for involvement. However, efforts to incorporate distance-learning principles into physical laboratory exercises have not yet led to a general mechanism or procedure for performing physical labs remotely. The opportunity to be able to fully cover physical laboratory exercises in distance learning setting would not only significantly enhance the student learning experience, it would also enable less privileged educational institutions to offer programs to a much broader target group of potential students who under no circumstances are able to travel and attend on-site sessions. In this paper, the authors present an overview of the field of remote or tele-operated physical laboratories how they can be implemented through today's technologies. Templates for developing a cohesive set of remote laboratories are identified along with Nemours IT considerations. In addition to the requirements related to technology, educational impacts are addressed. An example of a Control Systems experiment is then presented as an example of a functioning remote laboratory.

1. Introduction

The engineering students of yesterday have permanently changed the way we presently live and work with technology. It is essential that we take full advantage of their contributions in order to prepare the minds of the future. Advancements in telecommunication practices have made learning from remote locations viable, thereby granting access to information to people who would not otherwise have the privilege [1].

Distance learning has been implemented for decades and proven to be a viable alternative to traditional learning practices [2]. It works well for classes where predefined information is transferred from instructor to student, for example, history or basic math. A major bottleneck occurs when a student must obtain his or her own data through an experiment or laboratory work. It is important for a student to get hands-on learning to prepare them for a future in industry [3]. There is currently no system in place that allows a remote user to have the same experience as a student who is physically able to participate in an experiment. This hands on interaction is how participants develop essential problem solving skills. Many individual remote laboratory experiments have been created, but there has been little development on substituting an entire semester of labs [4].

A cohesive set of remote laboratory experiments needs to be created. This will provide justification for the implementation and validation of remote laboratories as an alternative to traditional practices. Successful setups give evidence to the practicality of remote laboratories and could help build consensus that they are a firm way to conform to Globalization 3.0, an era in which individuals collaborate and compete on a global level [5]. In this paper the authors discuss "templates" and associated implementation procedures that could assist in the creation of a semesters worth of remote laboratory experiments as usually offered in typical engineering laboratory courses. These templates should be viewed as a starting point, providing enough

information to start the lab building process but leaving enough freedom for adaptation for various circumstances.

There are two potential paths for developing remote laboratories. One involves the adaptation of current set-ups to be accessible via the internet. This could involve the adaptation of sensory inputs (webcams, microphones, thermometers...) and simple data-management inputs. Achieving this integration would allow the institution to provide use of the equipment for on-campus and off-campus students while avoiding most development costs. Due to the complex control of many procedures, this is not possible for every experiment. Since some procedures involve many steps that would not easily adapt to robotic control, the alternative path is to develop a new apparatus from scratch. An advantage to this approach is that the developer would be able to design the experiment with both audiences in mind.

2. Motivation and Scope

If proven successful, remote laboratories have the potential to engage more distance learning students. Many experiments could have equipment that does not require a lab assistant for anything but maintenance. These setups would allow access to equipment during all times of a day. A student's ability to work around a complex schedule would be eased if the schedule of lab availability were made available to potential participants.

Evidence of the capacity to integrate remote laboratory setups with traditional experiments needs to be shown before an institution can decide to put it to use [6]. Through the following Table 1, the authors wish to demonstrate the inclination of remote laboratory technology to be fused with current practices, and how measurement of success could be made.

Table 1: Outline for measuring the need for integration of remote laboratories

Driver	Metric
Distributed Education	Number of distance learning courses
Graduate Aptitude	On the job training requirements
Technological Advancement	Relevance of equipment and methodology to industrial practices
Specialized Equipment	Opportunities for interaction with industrial equipment
Increased Collaboration	Interaction and teamwork with geographically distributed individuals
Fiscal Limitations	Resources available for laboratories
Educational Impact	Test scores

Once the general understanding of the need for alternative educational techniques is presented, there must be a perception of how remote laboratories will resolve critical problems. The following Table 2 is an outline of the motivations and measurements of how and why to integrate remote laboratory technology with current practices.

Table 2: Outline for measuring the benefits of remote laboratories

Driver	Metric
Cost	Return on Investment Income Generation Potential
Process Efficiency	Effectiveness of Development Use with Local and Distant Students
Increased Process Speed	Time of Development
Workforce Reduction	Number of Automation Solutions Number of lab Assistants Needed
Workforce Aptitude	Increase of Advanced Degrees Technical Training aptitude
Product Lifecycle	Maintenance Cost / Time Number of Service Requests
Environmental Impact	Recycle / Reuse of Improvement Reduction of Equipment
Technological Advancement	Survey Experimental Results
Greater Accessibility	Communication Effort Automation Solutions
Access Time	Range of times equipment is available

Many universities and colleges lack the funding to provide extensive set-ups and are forced to compromise [4]. If an institution develops a remote laboratory program for their own uses, they could become a magnet school for others to use as a synergistic recourse. The host facility could collect a fee to cover maintenance and overhead, and the accessing entity would avoid development and storage costs.

Outside entities might also find an interest in this technology. Companies might wish to use it to train employees or test equipment before it is purchased [7]. High school students could also access a universities' equipment for advanced classes, while home schooled students would have access to unfamiliar equipment.

3. A Framework for Building a Remote Laboratory Program

In this section generalized approaches to developing and implementing remote laboratories for a university setting are addressed. A foundation that allows a novice to remote laboratory setups to understand the crux of the issue is desired, although there is no way to cover all the hypothetical situations. The breadth of these templates offered here is large enough to cover a cohesive set of a semester's worth of experiments.

3.1 Templates for remote laboratory implementation

Laboratory setups are similar to others in many ways [6]. Parallels between them can be used to group experimental setups into abstract collections that generalize the physical requirements of a lab. These collections can then model as templates for remote laboratory implementation procedures. The following list can be used to illustrate these generalized collections; Examples of common laboratory experiments and the field that might perform the procedures are included.

A few points need to be understood as this list is reviewed. The potential difficulty to incorporate a experiment with a remote laboratory setup increases as the list progresses. Creating a remote laboratory experiment is an art as much as it is science, leaving much room for interpretation. Many of the ideas overlap between templates, but they can still be used for problem framing exercises. And experiments that are similar across disciplines (such as Temperature effects) will still have critical differences in how the lesson is presented.

Electrical response/signal/display

Oscilloscope (Electrical)
Function Generation (Mechanical)
Amplification (Electrical)

Measurement

Temperature (Civil, Mechanical)
Sound/Light (Mechanical)
Current/Voltage/Power (Electrical)

Simple movement

Stress/Strain (Civil)
Physics experiments (Mechanical)
Pendulum effect (Mechanical)
Friction (Mechanical)

Complex movement

Controls laboratory (Electrical)
Vibrations (Civil)
Spring-Mass-Damper (Mechanical)
Tensile Test (Civil)

Mass Flow

Wave simulation (Civil)
Inlet/Outlet calculations

(Mechanical)

Air Flow/Heat Rates (Mechanical)
Viscosity (Mechanical)

Simulation*

Computer generated data (All)

*Simulation requires little to no modification to be used as a remote laboratory. There is a definite loss of user control/confidence with simulation [3] so in this paper we will not further discuss them as a viable alternative for a remote laboratory. Having said that, simulation is a powerful means to aid remote laboratories in many ways including pre-laboratory familiarization with equipment, developing a better understanding of theoretical fundamentals and expectations toward the outcome of an experiment, etc.

Electrical response/signal/display

Many basic experiments deal with the understanding of signals and how they are created. Students currently toggle buttons and alter switches on various apparatuses like function generators and view the response on an oscilloscope. Technology exists that allows a student to control these machines and others via a computer connection, usually USB [8]. Assuming there is no need to alter connections, the best case scenario allows the equipment to be accessed through remote desktop software. If altering the equipment is necessary (for example, switching polarities of a diode), a robot could be programmed to handle this task, or much more simply, have a lab assistant make the switch. More information on the use of a lab assistant will follow.

Measurement

Many forms of measuring equipment are available in digital forms, allowing simple assimilation with computers. If there is a reason to avoid computer-equipment integration, cameras can be used to monitor a display. An experiment can be designed to give a student control, while fixing certain parameters. Students can then take the data derived from their observations and crunch the numbers. Take the example of measuring the speed of light. The setup has fixed distances between signal origin and receiver, but allows the student control of the output. In this case, the students still need to apply critical reasoning skills, but most of the data is available on their computer screens [10].

Simple Movement

Experiments that require simple flick of a mass, pull of a bar, or opening of a gate can be assisted by a simple actuator like a solenoid or an electric motor. The speed or power of an articulation can be controlled through various methods, allowing variance when required.

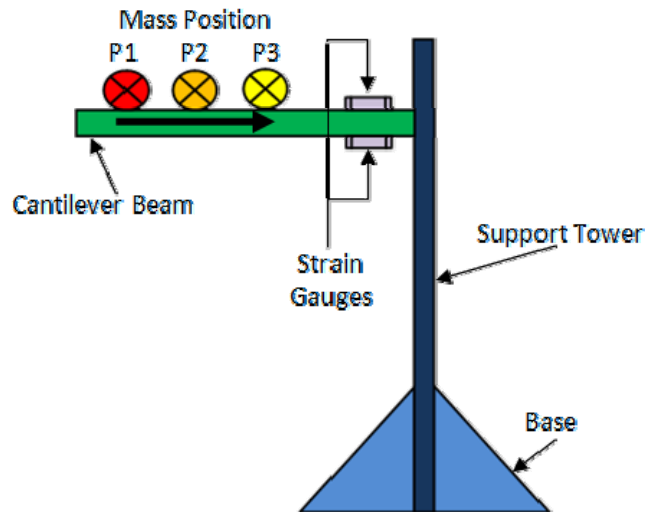


Figure 1: Use of a remote controlled mass to alter stress on a beam

In this example (see Figure 1), a cantilever beam is affixed with strain gauges to measure the effect of a change the mass position. Control can be maintained by a single motor that translates the mass moved toward and away from edge of the beam. The mass of the object, wires, and motor as well as the other constants could be given to the students, and it would be up to them to calculate the bending moment.

Complex Movement

Success in engineering requires an understanding in complex systems. We cannot limit the scope of remote laboratories to only simple setups. Those with more intricate movements or relationships will require more robotic intrusion than the others and possibly a lab assistant to initiate steps or replace components.

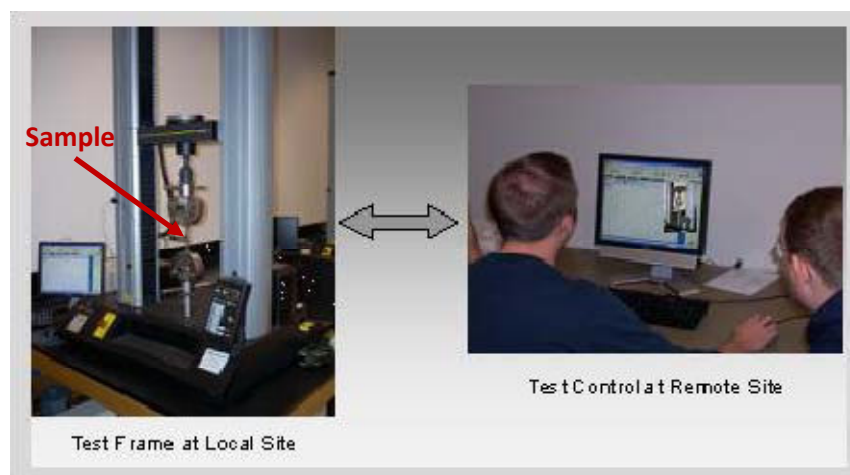


Figure 2: A Remote Laboratory for Tensile Testing

In this example of a simple tensile test (see Figure 2), Remote desktopping software can be used to control the machine, and receive all pertinent data. A lab assistant would need to replace the sample after it reaches critical failure [4]. A prefabricated machine with built in computer control such as this one makes integration easy. Many complex setups will require much more adaptation, rebuilding, or monitoring to be practical as a remote laboratory than what was required here [10]. An example of how a multi-dimensional robot was used to model a controls experiment and how it can be used to evaluate it as a remote laboratory is available in the appendix.

Mass Flow

Mass flow also involves complex movement of matter, but the containment and travel of water or air places these setups in their own class. All remote labs should include safety measures. Mass flow labs need not only to contain the working fluid, but when elevated temperatures or pressures are needed, it is especially important to create failsafe mechanisms to guarantee the safety of the equipment and possible staff.

3.2 Technical requirements

Measurement and signal response setups are less time dependant than those with movement, so time consideration is less important for them. Many institutions have multiple firewalls for data to traverse, slowing it down. A small bandwidth could also negatively affect response times. For a remote laboratory to be successful, the lag between locations must be minimal. It is assumed that there will be no information technology shifts within the host or remote organization, but there are a few methods to avoid unwanted lag or communication failure. These are:

1. Ensure the appropriate system settings and ports are opened in the remote and host location. This includes altering computer and network firewalls.
2. Operate laboratories on high performance computers, especially advanced video cards.
3. Connect the apparatus directly with a server. This can be done with portable dedicated web servers.
4. Use a Command and Control station. This allows direct connection between host and remote users. Some portable servers can be used as a Command and Control unit.

Specific procedures vary depending on the laboratory requirements and institution policies. Thus, more specific instructions that generally apply across the board cannot be made here. Various methods have been patented to facilitate this connection between networks for needs such as remote laboratories [12]. The simplest way found to securely connect computers is to use remote desktop software. Windows comes with a built in remote desktop function, but this removes control from the host computer. Freeware programs like Real VNC allow for specific port mapping, but are not as friendly as subscription services like Yugma.

3.3 Preparing the students

Distance learning students should already contain the attributes needed for success with the medium. In short, they should be self-driven, have the ability to organize information, and take initiative [13]. Remote laborites should be made to conform to the guidelines of distance education to allow all participants to get a similar experience as those who can participate in person.

Students should get the necessary background information and prelabs in the same period as with traditional practices [3]. There should be no need for special training, as they should already be competent with simple computer functions like moving a mouse and inputting commands from the keyboard. An open mind is to allow them to interpret their observations as if they were with the apparatus they are working on.

There is no need for a uniquely structured handout or report structure since many current laboratory practices involve a final submission of a typed report or worksheet completion. Laboratory manuals themselves must be detailed enough to provide the students with enough instruction to work independently. If there is a roadblock that the participants cannot overcome, a teaching assistant could be utilized for assistance through instant messaging software.

3.4 Implementation

Need for a lab assistant or teaching assistant will vary between experiments. Interference from any sources other than the remote participants and the laboratory apparatus during the lab should be avoided if possible. An optimum remote lab setup can be accessed at any time of the day. Having the need to staff the apparatuses limits this and negatively effects overhead. Occasional maintenance should be expected. If it is unavoidable to forgo the use of an assistant, their services could be used for a number of tasks:

- Resetting equipment
- Tripping breakers
- Replacing parts
- Moving cameras/microphones
- Alter connections
- Fixing system malfunctions
- Assist remote users through communication software
- Clean up

3.5 Pedagogical Requirements

Every student learns differently. Some are more suited to learn visually, while others can only get the full impact by using their hands. The same material can have completely different meaning to these people. Laboratory experiments speak to those who require tactile feedback, although students benefit from kinesthetic learning [13]. The student experiences build off each other and work to provide a holistic view as to how to understand a problem.

Table 3: List of learning styles and their respective strengths

Learning Styles	Strengths
Convergent	Practical application of Ideas
Divergent	Imaginative ability and generation of ideas
Assimilation	Creating theoretical models and making sense of disparate observations
Accommodative	Carrying out plans and that involve them in new experiences

Going beyond the idea of hands on learning, in the above Table 3 the positive attributes of more method based learning traits are shown. Remote Laboratory experiments should always cover each of these categories. Convergent thinkers are able to benefit from the fact that there is no simulation; every input has a direct output. The imagination required to understand that the image or data on a screen is changing in real-time, benefiting the divergent oriented minds to think of the experiment as a whole. Assimilation is gained through most laboratory procedures, local or remote, when the students are asked to understand what is happening, draw figures, or interpret the results. Similarly, accommodative learning occurs when the student is first introduced to a procedure. Remote laboratories have the advantage of delivering another step for the students to conceptualize.

The principle method used for the example remote laboratory in the appendix was based on outcome based learning ideas. The tasks aimed to prove that those involved with the experiment have been able to internalize the intended material by giving answers to specific questions and feedback.

Positive Effects of Outcome Based Learning

- Makes learning focused and achievable
- Gives direction to student learning
- Provides a positive contract between the teacher and student, avoiding digressions
- Allows for specific intervention if objectives are not met
- Allows for flexibility in learning areas
- Helps to focus on essential concepts and skill in the subject
- Possible increase learning

Negative Outcomes of Outcome Based Learning

- Focus on measurable objectives to the neglect of attitudes, values, motivation and interest
- Focus too narrowly on minutiae, which can trivialize learning
- Are difficult and time consuming to write
- Are teacher-centered
- Limit opportunities from spontaneous unintended outcomes occurring during learning experiences
- Result in educational achievements being confounded by issues of accountability

Note: The table and lists in this section are renovated quotes from [13]:

4. Closing Remarks

In a world where distance learning is rapidly becoming a major component to the educational landscape, it is important to make the most of available technology. Robotic control through the internet is an effective and reliable way to operate remote laboratories. This is the next step in the evolution of distance learning. Its implementation is a matter of building an apparatus and comparing it with traditional practices. Once this has developed enough, remote laboratories will garner economical and collaborative opportunities between institutions. Future works will provide and assessment and evaluation of remote laboratories based of the templates presented in this paper and address the pedagogical differences between experiments in more thorough detail.

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Appendix: Controls Remote Laboratory with a Multi-Axis Robot

A1. Lesson Plan

Introduction

This lesson was created to functionalize as a procedure for students to follow as well as serve as a tool to gain understanding of remote laboratory creation for the researchers. It has yet to be tested in a by students as a graded assignment, but preliminary assessments show potential to be integrated into a mechanical engineering curriculum. Controls is a complicated subject matter that requires visualization to comprehend the effect on the system when certain parameters are altered [14]. This was achieved by including a camera and microphone with the setup. It was assumed that the students had already possessed the mathematical background for, or taken a taken a course in Controls.

Student Background information/Science

A proportional–integral–derivative controller (PID controller) is a generic controller widely used in industrial control systems. A PID controller attempts to correct the error between a measured process variable and a reference input by calculating and then outputting a corrective action that can adjust the process accordingly.

The PID controller involves three separate parameters; the Proportional, the Integral and Derivative values. The Proportional value determines the reaction to the current error, the Integral value determines the reaction based on the sum of recent errors, and the Derivative value determines the reaction based on the rate at which the error has been changing. The weighted sum of these three actions is used to adjust the process via an actuator. By "tuning" the three constants in the PID controller algorithm, the controller can provide control action designed for specific process requirements. The response of the controller can be described in terms of the responsiveness of the controller to an error, the degree to which the controller overshoots the reference and the degree of system oscillation.

Some applications may require using only one or two modes to provide the appropriate system control. This is achieved by setting the gain of undesired control outputs to zero. A PID controller will be called a PI, PD, P or I controller in the absence of the respective control actions. PI controllers are particularly common, since derivative action is very sensitive to measurement noise, and the absence of an integral value may prevent the system from reaching its target value due to the control action.

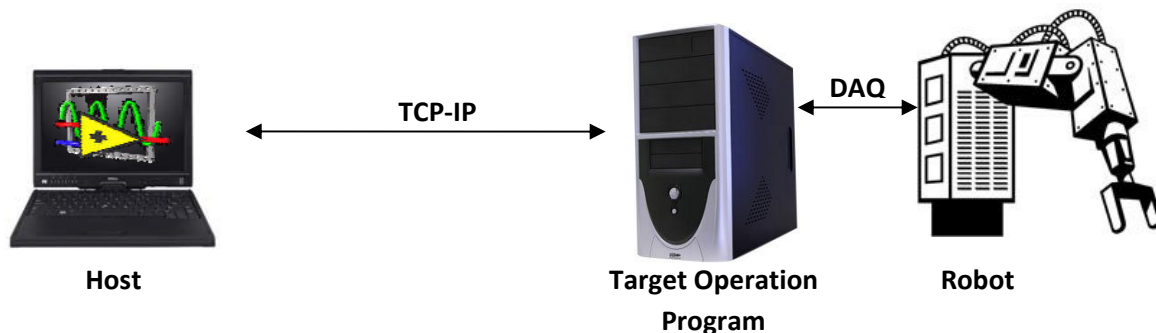


Figure A1: Simplification of robot control through an external program

Robotic systems consist of a complex network of actuators and sensors. However, these components themselves are incredibly simple. In a general robotic system, each joint contains a drive and an encoder. The drive initiates motion of the joint and the encoder measures the displacement of the joint in order to determine the robot's exact position in space. PID controllers are often used to close the loop around these drives via the encoder signal and ensure the robot travels to its commanded position while satisfying the requisite performance characteristics.

These joints are controlled concurrently to produce the desired end effector trajectory (the translation of the load). This motion is coordinated by a slave or target, which is a dedicated computer, which receives the user's commands from a host computer and translates these instructions into control inputs to the drives of each joint. The host computer is the point of interaction for the user, and is at any given time in direct communication with the slave. For this laboratory you will be exploring a system similar to this. However the host system is located at a remote location. Thus, you will use distance learning tools to set up a remote terminal to the host computer so that you may be in direct control of the robot.

Set-up instructions

To gain the best chance of maintaining a stable connection, the following instructions must be adhered to. Notes for possible reasons for error are included with the pertinent steps.

Communications protocol

1. Open a dedicated port *if it is independent from other ports, there will be no conflicting data flow causing a connection interruption.*
 - a. On the network supporting the robot (Host Network)
 - b. On the computer supporting the robot (Host Computer)
The dedicated port must be the same for the network and computer. A network administrator is usually required to handle this task.
2. Open firewall settings
 - a. Allow the firewall to open communication in for the dedicated port
 - b. Allow the use of Microsoft Remote Desktop
Different operating systems have different ways to allow Remote Desktop Access. A network administrator will be able to quickly complete this task. MAC has a remote desktop function that has the potential to work, but is not seamlessly compatible with Windows systems.

Robotic Apparatus Preparation

1. Allow the host computer to run on a fresh boot up
2. Open Controls program
Remote users can open the program, but it is best to be done by a host supervisor due to complications which may arise from the time delays.
3. Turn on the robot and leave in standby mode
This is assuming it is functioning properly. Currently, a supervisor in the host location must do this step.
4. It is optional to test the functionality of the robot from the host location to ensure the apparatus can be controlled remotely with the current setup

Remote Access

1. Identify host computers IP Address
2. Open Remote Desktop on computer seeking to access robot (Remote Computer)
3. Enter Host Computer IP Address and dedicated port number in the format:
“IP Address::port number” for example 12.34.456.89::1234

This should turn the host computer monitor black and bring up a login screen on the remote computer. If there is no login information, it must be set up on the host computer, requiring the user to restart step 3.

Once the remote computer has access, they will be able to control the robot as if they were on the host computer.

There will be a variable time delay in control and perception of response subject to host and remote network traffic.

Experimental Procedures

1. Understanding the apparatus
 - a. Click to the Trajectory Generation tab
 - b. Set the X-axis to output a Sawtooth function and the Y-axis to output a Square wave function
 - c. Set the X-amplitude to appx 15 cm and the Y-amplitude to appx 20 cm
 - d. Set the X-frequency to appx 2.5Hz and the Y-frequency to appx 2 Hz
 - e. The screen should appear similar to the following figure

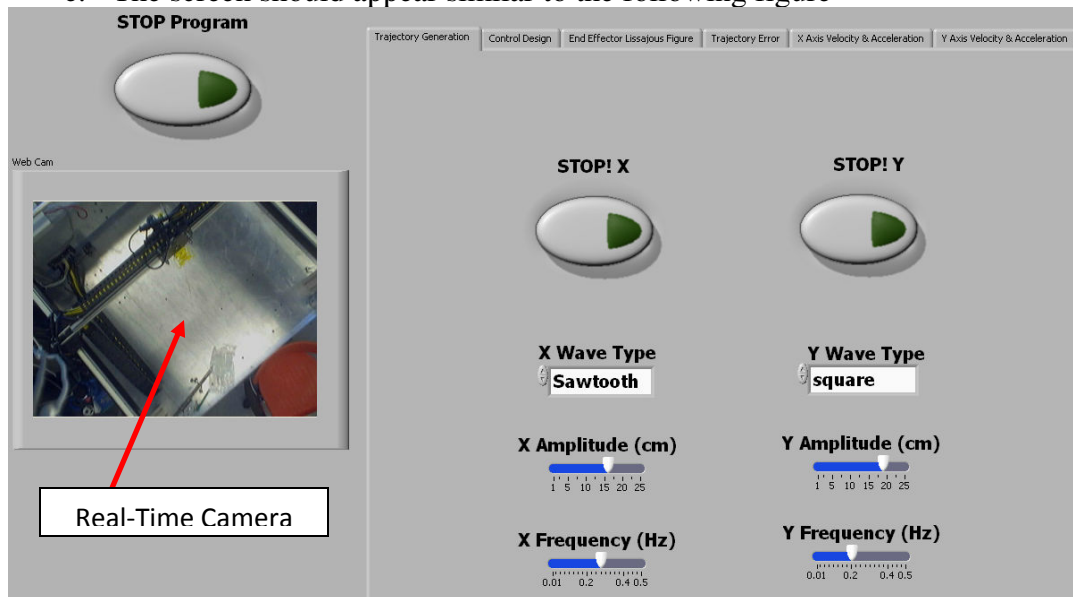


Figure A3: Representation of initial experimental setup screen

- f. Turn on both axes
- g. Familiarize yourself with the other tabs
- h. Change the values in the Control Design tab and note any changes in the Trajectory Error tab
- i. Reset the figure in the End Effector tab and verify that the head of the robot is synced with the repose indicated in the graph.

- i. It may be necessary to adjust the X and Y amplitudes and frequencies to be able to clearly notice the responses
 - ii. Use the video and sound of the robot to compare with the end effector readings
 - j. Test the response time of the robot by turning one axis off and adjusting the other on or off.
 - i. Note the time required for the video to change using a stopwatch
 - ii. Note the time required for the end effector to change
 - k. Turn both axes off
2. Error reduction in the X axis
 - a. Set the X wave type to sine
 - b. Set all other inputs to their middle value
 - c. Turn on the X axis
 - d. Use trial and error to reduce the error in the x axis as much as possible and note the values
 - e. Use the question in the following figure to calculate the theoretical output
 - f. Calculate the gains which theoretically result in the least error
 - g. Set the gain to the calculated value
 - h. Turn off the X axis

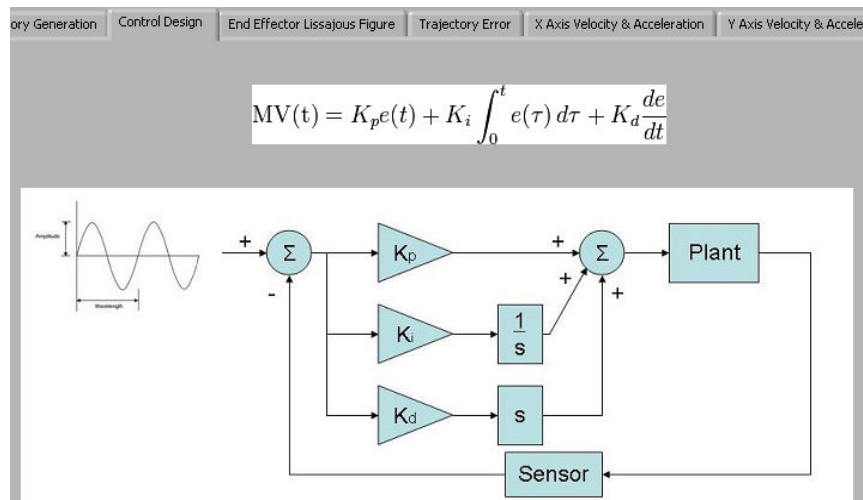


Figure A4: Equations and simplified response schematic

3. Error reduction in the Y axis
 - a. Set the Y wave type to sine
 - b. Set all other inputs to their middle value
 - c. Turn on the Y axis
 - d. Use trial and error to reduce the error in the Y axis as much as possible and note the values
 - e. Calculate the theoretical output with these values
 - f. Calculate the gains which theoretically result in the least error
 - g. Set the gain to the calculated value
 - h. Turn off the Y axis
 - i. Note any results that differ from the previous experiment

4. Error reduction in the both axes
 - a. Set both wave type to sine
 - b. Set all other inputs to their middle value
 - c. Turn on the Y axis
 - d. Use trial and error to reduce the errors as much as possible and note the values
 - e. Calculate the theoretical output with these values
 - f. Calculate the gains which theoretically result in the least error
 - g. Set the gain to the calculated value
 - h. Turn off both axes
 - i. Note any results that differ from the previous two experiments
5. Types of damping
 - a. Set the X axis to a square wave
 - b. Set the X frequency to 0.1
 - c. Set the X amplitude to 25
 - d. Use trial and error by adjusting the gains to create a response that appears to be over damped, verify with calculations
 - e. Calculate a gain combination that will result in an under damped response, verify with the error output
 - f. Calculate a gain combination that will result in an critically damped response, verify with the error output
 - g. Turn off both axis

Creativity Exercises

Student will have the option to choose one of the following exercises

1. Alternative methods
 - Repeat one of experiments 2-4 using a any combination of a square wave or sawtooth function
2. Visualization
 - Use any combination of the inputs including wave functions to create at least 5 interesting result in the end effector response screen. An example is making a near perfect circle
 - Device a way to represent aliasing and describe why and how this could affect the results in this experiment, if at all
3. New design
 - Using your background of control system, create an outline for a new experiment using the available tools

Clean up Instructions

1. Stop all motion on the robot
2. Click the 'x' on the top of the screen to relinquish control of the host computer
Depending on the situation (Others waiting to connect, last experiment of the day...) it might best to shut down the computer remotely, which will automatically relinquish control.

Survey for Improvement*

Please circle the result that best fits your experience

How well could you understand the instructions?

They gave too
much
information

More detail
would have been
helpful

They were
adequate

There was not
enough
information

How do you feel experience relates to other experiments you have done?

This seemed
like a video

There was not
enough
interaction

It felt the
similar, but
less hands-on

There were
some benefits
and failures

It felt
exactly the
same

It felt more
beneficial

How would you rate the visual impact of the program?

I could not understand
the layout and the
video was hard to see

I understood what was
happening, but needed
to concentrate

It was alright, but
lacking something
important

I got the same
experience as if I was
with the apparatus

How would you rate the audio impact of the program?

I could not
understand what I
was hearing

The sounds were too
distinct from what I was
seeing

I heard and saw
the same actions

It was a comfortable
way to interact with the
robot

Please circle all that apply

How would you classify the user interface?

Impossible to
understand

Complicated yet
functional

Too much visual
stimulus

Concise and
practical

What did you think of the controllable functions?

Too many
options

Not enough
options

Difficult to
manipulate

Easy to work
with

What suggestions could you make to improve this experiment?

*Survey results will be issued in subsequent publications.